

Electroweak moments of baryons and hidden strangeness of the nucleon.¹

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Abstract

The phenomenological sum-rule-based approach is used to discuss the quark composition dependence of some static electroweak characteristics of baryons. The role of nonvalence degrees of freedom (the sea partons and/or peripheral meson currents) is shown to be important to select and make use of the relevant symmetry parametrization of baryon observables. The implications of the baryon magnetic moment analysis for estimation of the Δ_q , ($q = u, d, s$), values of the spin-dependent DIS on nucleons, the contribution of hidden strangeness to the nucleon magnetic moment and to the quark-line-rule violating $\phi\pi$ -production in antinucleon-nucleon annihilation reaction are presented.

1 Outline and summary of sum rule approach to $\mu(B)$

The rapidly growing precision of measurements of the electroweak coupling constants, like magnetic moments or the G_A/G_V - ratios in baryon semi-leptonic decays [1, 2, 3], may be the basis of new, more subtle and detailed information on the internal structure of baryons. In this report we consider some consequences of sum rules for the static, electroweak characteristics of baryons following from the theory of broken internal symmetries and common features of the quark models including relativistic effects and corrections due to nonvalence degrees of freedom – the sea partons and/or the meson clouds at the periphery of baryons.

In Ref. [4, 5], the following parametrization was introduced for magnetic moments $\mu(B)$ of baryons :

$$\mu(B) = \mu(q_e)g_2 + \mu(q_o)g_1 + C(B) + \Delta, \quad (1)$$

$$\mu(\Lambda) = \mu(s)\left(\frac{2}{3}g_2 - \frac{1}{3}g_1\right) + (\mu(u) + \mu(d))\left(\frac{1}{6}g_2 + \frac{2}{3}g_1\right) + \Delta, \quad (2)$$

$$\mu(\Lambda\Sigma) = \frac{1}{\sqrt{3}}(\mu(u) - \mu(d))\left(\frac{1}{2}g_2 - g_1\right) + C(\Lambda\Sigma), \quad (3)$$

$$\Delta = \sum_{q=u,d,s} \mu(q)\delta(N), \quad (4)$$

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where $\mu(q)$ are the effective quark magnetic moments defined without any nonrelativistic approximations, $q_e = q_{even} = u; d; s$ for P and Σ^+ ; N and Σ^- ; Ξ^0 and Ξ^- , $q_o = q_{odd} = u; d; s$ for N and Ξ^0 ; P and Ξ^- ; Σ^+ and Σ^- , respectively, so that $P = u^2d$, $N = d^2u$, etc. if only valence quarks are retained, $g_{2(1)}$ are "reduced" dimensionless coupling constants obeying exact $SU(3)$ -symmetry and related with the $SU(3)$ F - and D - type constants via $g_2 = 2F$ and $g_1 = F - D$, $\delta(B)$ is a matrix element of the OZI-suppressed $\bar{q}q$ -configuration for a given hadron: $\delta(B) = \langle B | \bar{q}q | B \rangle$, where $q \notin \{q_e^2, q_o\}$, e.g. $\delta(N) = \langle N | \bar{s}s | N \rangle$, etc. For the models, explicitly including the meson degrees of freedom, we introduce the exchange current contribution to $\mu(B)$ due only to the dominant pion currents (these contributions are represented by the diagrams with the photon touching the charged pion line that connects different nonstrange quark lines). By inspection, this contribution is absent for all octet, three-quark hyperons except for the nondiagonal $\mu(\Lambda\Sigma)$ -magnetic moment. So that $C(P) = -C(N)$ and $C(\Lambda\Sigma)$ are the isovector contributions of the charged-pion exchange current to $\mu(P), \mu(N)$ and the $\Lambda\Sigma$ -transition moment $\mu(\Lambda\Sigma)$. In the following we make use, consecutively, two pictures of the baryon internal composition. In the first one, all baryons are considered as consisting of three massive, "dressed" constituent quarks, locally coupled with lightest goldstonions – the pion fields. In the second picture only fundamental QCD quanta – the quarks and gluons – are there, the meson component of the baryon state vectors being represented by the properly correlated "current" quarks and gluons. The use of one picture or another will be reflected in a particular parametrization of contributions due to corresponding nonvalence degrees of freedom. Below, we shall use the particle and quark symbols for corresponding magnetic moments. Equations (1) – (4) lead to the following sum rules [4, 5]:

$$P + N + \Xi^0 + \Xi^- - 3\Lambda + \frac{1}{2}(\Sigma^+ + \Sigma^-) = 0, \quad (5)$$

$$(\Sigma^+ - \Sigma^-)(\Sigma^+ + \Sigma^- - P - N) - (\Xi^0 - \Xi^-)(\Xi^0 + \Xi^- - P - N) = 0, \quad (6)$$

$$\alpha = \frac{D}{F + D} = \frac{g_2 - 2g_1}{2(g_2 - g_1)} = \frac{1}{2} \left(1 - \frac{\Xi^0 - \Xi^-}{\Sigma^+ - \Sigma^- - \Xi^0 + \Xi^-} \right), \quad (7)$$

$$C(P) = \frac{1}{2}(C(P) - C(N)) = \frac{1}{2}(P - N + \Xi^0 - \Xi^- - \Sigma^+ + \Sigma^-), \quad (8)$$

$$C(\Lambda\Sigma) = \mu(\Lambda\Sigma) + \frac{1}{\sqrt{3}}(\Xi^0 - \Xi^- - \frac{1}{2}(\Sigma^+ - \Sigma^-)), \quad (9)$$

$$\frac{u - d}{u - s} = \frac{\Sigma^+ - \Sigma^- - \Xi^0 + \Xi^-}{\Sigma^+ - \Xi^0}, \quad (10)$$

$$\frac{u}{d} = \frac{\Sigma^+(\Sigma^+ - \Sigma^-) - \Xi^0(\Xi^0 - \Xi^-)}{\Sigma^-(\Sigma^+ - \Sigma^-) - \Xi^-(\Xi^0 - \Xi^-)}, \quad (11)$$

$$\frac{s}{d} = \frac{\Sigma^+\Xi^- - \Sigma^-\Xi^0}{\Sigma^-(\Sigma^+ - \Sigma^-) - \Xi^-(\Xi^0 - \Xi^-)}, \quad (12)$$

$$\Delta^{++} = \frac{u}{s}\Omega^- = \frac{u}{d}\Delta^{--}. \quad (13)$$

Reserving the possibility of $g_i(N) \neq g_i(Y)$, $Y = \Lambda, \Sigma, \Xi$, due to a more prominent role of the pion degrees of freedom in the nucleon and combining Eqs. (5)–(6), we propose also the following, probably, most general sum rule of this approach

$$\begin{aligned} &(\Sigma^+ - \Sigma^-)(\Sigma^+ + \Sigma^- - 6\Lambda + 2\Xi^0 + 2\Xi^-) \\ &-(\Xi^0 - \Xi^-)(\Sigma^+ + \Sigma^- + 6\Lambda - 4\Xi^0 - 4\Xi^-) = 0. \end{aligned} \quad (14)$$

Eqs.(11) – (13) are obtained provided $\delta(N) = 0$. Hence, we relate them to the chiral constituent quark models, where we assume that a given baryon consists of three "dressed" constituent quarks, and also to the validity of the OZI (or the quark–line) rule. Now, we list some consequences of the obtained sum rules. By definition, the Λ -value entering into Eqs. (5) and (14) should be "refined" from the electromagnetic $\Lambda\Sigma^0$ -mixing affecting $\mu(\Lambda)_{exp}$. Hence, the numerical value of Λ , extracted from Eq. (14), can be used to determine the $\Lambda\Sigma^0$ -mixing angle through the relation

$$\sin \theta_{\Lambda\Sigma} \simeq \theta_{\Lambda\Sigma} = \frac{\Lambda - \Lambda_{exp}}{2\mu(\Lambda\Sigma)} = (1.43 \pm 0.31)10^{-2} \quad (15)$$

in accord with the independent estimate of $\theta_{\Lambda\Sigma}$ from the electromagnetic mass-splitting sum rule [6]. Equation (11) shows that owing to interaction of the u - and d - quarks with charged pions the "magnetic anomaly" is developing, i.e. $u/d = -1.80 \pm 0.02 \neq Q_u/Q_d = -2$. Evaluation of the lowest order quark–pion loop diagrams gives [7]: $u/d = (Q_u + \kappa_u)/(Q_d + \kappa_d) = -1.77$, where κ_q is the quark anomalous magnetic moment in natural units. The meson–baryon universality of the quark characteristics, Eqs. (10) – (12), suggested long ago [8], is confirmed by the calculation of the ratio of K^* radiative widths

$$\frac{\Gamma(K^{*+} \rightarrow K^+\gamma)}{\Gamma(K^{*+} \rightarrow K^+\gamma)} = \left(\frac{u/d + s/d}{1 + s/d} \right)^2 = 0.42 \pm 0.03 \text{ (vs } 0.44 \pm 0.06[1]). \quad (16)$$

The experimentally interesting quantities $\mu(\Delta^+P) = \mu(\Delta^0N)$ and $\mu(\Sigma^{*0}\Lambda)$ are affected by the exchange current contributions and for their estimation we need additional assumptions. We use the analogy with the one-pion-exchange current, well-known in nuclear

physics, to assume for the exchange magnetic moment operator

$$\hat{\mu}_{exch} = \sum_{i < j} [\vec{\sigma}_i \times \vec{\sigma}_j]_3 [\vec{\tau}_i \times \vec{\tau}_j]_3 f(r_{ij}), \quad (17)$$

where $f(r_{ij})$ is a unspecified function of the interquark distances, $\vec{\sigma}_i(\vec{\tau}_i)$ are spin (isospin) operators of quarks. Calculating the matrix elements of $\hat{\mu}_{exch}$ between the baryon wave functions, belonging to the 56-plet of $SU(6)$, one can find

$$C(P) = \frac{1}{\sqrt{2}} C(\Delta^+ P) = \sqrt{3} C(\Lambda \Sigma), \quad (18)$$

$$\mu(\Delta^+ P; \{56\}) = \frac{1}{\sqrt{2}} \left(P - N + \frac{1}{3}(P + N) \frac{1 - u/d}{1 + u/d} \right). \quad (19)$$

where Eq.(19) may serve as a generalization of the well-known $SU(6)$ -relation [9]. We close this section presenting the set of sum rules following from Eqs.(2)–(4) with $C(B's) = \delta(B's) = 0$, $u/d = -2$:

$$\Sigma^+[\Sigma^-] = P[-P - N] + (\Lambda - \frac{N}{2})(1 + \frac{2N}{P}), \quad (20)$$

$$\Xi^0[\Xi^-] = N[-P - N] + 2(\Lambda - \frac{N}{2})(1 + \frac{N}{2P}), \quad (21)$$

$$\mu(\Lambda \Sigma) = -\frac{\sqrt{3}}{2} N. \quad (22)$$

The numerical values of Eqs.(20)–(22) coincide almost identically with the results of the $SU(6)$ -based NRQM taking account of the $SU(3)$ breaking due to the quark-mass differences [8]. We stress, however, that no NR assumption or explicit $SU(6)$ -wave function are used this time. The ratio α (cf. Eq.(7)) equals .61 in this case, demonstrating a substantial influence of the nonvalence degrees of freedom on this important parameter.

In calculations we used baryon magnetic moments from the PDG-tabulation [1] and new values of the $\mu(\Xi^-)$ and $\mu(\Sigma^+)$, from [2] and [3], respectively.

2 The OZI-rule violation in magnetic and axial couplings of baryons

Here, we follow a complementary view of the nucleon structure, absorbing $C(N's)$ into products of the corresponding $\mu(q)$ and $g(N's)$, keeping the constraint $u/d = -2$, and $\delta(B's)$ non-zero. We shall refer to this approach [10] as a correlated current quark picture of

nucleons. Then, instead of Eq.(11) we have (in n.m.)

$$\Delta(N) = \frac{1}{6}(3(P + N) - \Sigma^+ + \Sigma^- - \Xi^0 + \Xi^-) = -.07 \pm .01, \quad (23)$$

$$\mu_N(\bar{s}s) = \mu(s)\langle N|\bar{s}s|N\rangle = (1 - \frac{d}{s})^{-1}\Delta = .13, \quad (24)$$

where independence of the sum $P+N$ of the $C(N$'s) and the ratio $d/s=1.55$ from the correspondingly modified Eq.(12) were used. By definition, $\mu_N(\bar{s}s)$ represents the contribution of strange ("current") quarks to nucleon magnetic moments. Numerically, Eq.(24) agrees fairly well with other more specific models (see,e.g. [11]). The calculated quantity indicates violation of the OZI rule and the strange current quark contribution $\mu_N(\bar{s}s)$ is seen to constitute a sizable part of the isoscalar magnetic moment of nucleons (or, which is approximately the same, of the nonstrange constituent quarks)

$$\frac{1}{2}(P + N) = \mu(\bar{u}u + \bar{d}d) + \mu(\bar{s}s) = .44, \quad (25)$$

This observation helps to understand the unexpectedly large ratio [12]

$$BR\left(\frac{\bar{P}N \rightarrow \phi + \pi}{\bar{P}N \rightarrow \omega + \pi}\right) \simeq (10 \pm 2)\%, \quad (26)$$

reported for the s -wave $\bar{N}N$ - annihilation reaction.

Indeed, the transition $(\bar{P}N)_{s-wave} \rightarrow V + \pi$, where $V = \gamma, \omega, \phi$, is of the magnetic dipole type. Therefore, the transition operator should be proportional to the isoscalar magnetic moment contributions from the light u - and d -quarks and the strange s -quark, Eq.(25). The transition operators for the ω - and ϕ -mesons are obtained from $\mu(\bar{q}q)$ and $\mu(\bar{s}s)$ through the well-known vector meson dominance model (VDM). Using the "ideal" mixing ratio $g_\omega : g_\phi = 1 : \sqrt{2}$ for the photon-vector-meson junction couplings and $\mu_\omega : \mu_\phi = \mu(\bar{q}q) : \mu(\bar{s}s)$ according to Eq.(24) and Eq.(25), we get

$$BR\left(\frac{\bar{P}N \rightarrow \phi + \pi}{\bar{P}N \rightarrow \omega + \pi}\right) \simeq \left(\frac{\mu(\bar{s}s)}{\sqrt{2}\mu(\bar{u}u + \bar{d}d)}\right)^2 \left(\frac{p_\phi^{c.m.}}{p_\omega^{c.m.}}\right)^3 \simeq 6\%, \quad (27)$$

which is reasonably compared with data.

The structure constants connected with the vector part of the weak neutral current (NC) are obtained from the electromagnetic ones by the substitution

$$Q(q) \rightarrow V^{NC}(q) = \frac{1}{2\sin\theta_W\cos\theta_W}(t_L(q) - 2Q(q)\sin^2\theta_W), \quad (28)$$

where $Q(q)$ is the quark electric charge, t_L —the 3rd component of the weak isospin, $\sin^2\theta_W = .23$, θ_W —the weak angle. In this way, for the NC analogue of magnetic moments of the proton, neutron and deuteron we get (in the units of n.m.)

$$\mu^{NC}(P) \simeq 1.49(1.25), \quad (29)$$

$$\mu^{NC}(N) \simeq -1.52(-1.73), \quad (30)$$

$$\mu^{NC}(d) \simeq -0.04(-.47), \quad (31)$$

where the values in the parentheses refer to the neglect of the strange quark contributions. Therefore the planned detailed investigation of the $\gamma - Z^0$ interference effects and measuring $\mu_N(\bar{s}s)$ via the P- odd effects in polarized electron–nucleon scattering [11] will give an important information on the strangeness content of the nucleon.

The value of $\langle N|\bar{s}s|N \rangle$ in Eq.(25) can be considered as the difference of the averaged values $\langle N|l_z(s) + \sigma_z(s)|N \rangle$ of strange quarks and antiquarks, respectively, $l_z(s)$ and $\sigma_z(s)$ being the orbital and spin operators of corresponding quarks in the polarized nucleon. The product of this combination of the quark angular momenta and the effective magnetic moments of quarks, in which quark energies are used instead of quark masses, was proposed [13] to define the magnetic moment operator in a relativistic model of quark composites. Taking, for the sake of qualitative estimates, $\mu(s) = -e/(6\varepsilon_s) \simeq -.7$ n.m., where we put $\varepsilon_s \simeq (m_s^2 + p_s^2)^{\frac{1}{2}}$, $m_s(\simeq 150MeV)$ – the "current" quark mass, $p_s(\simeq 400MeV)$ —the mean momentum of sea quarks, we obtain

$$\sum_{s,\bar{s}} \langle N, J_z = +\frac{1}{2} | \sigma_z(s) + l_z(s) - \sigma_z(\bar{s}) - l_z(\bar{s}) | N, J_z = +\frac{1}{2} \rangle \simeq -.17, \quad (32)$$

which can be compared with the other strange quark spin characteristics $\Delta s \simeq -.1$, as given by the polarized DIS data, e.g. [14]. We wish here to note the following alternative. As is known [14], to obtain the contributions of the u,d-, and s-flavoured quarks to the proton spin, denoted by $\Delta u(p)$, $\Delta d(p)$ and $\Delta s(p)$, the use is usually made of baryon semileptonic weak decays treated with the help of the exact $SU(3)$ -symmetry. It has been shown earlier [15, 16] that when both the strangeness-changing ($\Delta S = 1$) and strangeness-conserving ($\Delta S = 0$) transitions are taken for the analysis, then $(D/F + D)_{ax}^{\Delta S=0,1} = .635 \pm .005$ while $(D/F + D)_{ax}^{\Delta S=0} = .584 \pm .035$, which is close to $(D/D + F)_{mag} \simeq .58$, according to Eq.(7). We list below two sets of the Δq -values, we have obtained from the data with inclusion of the QCD radiative corrections (e.g.[14] and references therein) :

$\Delta u(p) \simeq .82(.83)$, $\Delta d(p) \simeq -.44(-.37)$, $\Delta s = -.10 \pm .04(-.19 \pm .05)$, where the values in the parentheses correspond to $\alpha_D = (D/D + F) = .58$. At the same time, the problem of difference of the following two expressions

$$F - D = \Delta d(p) - \Delta s(p) = G_A^{exp}(\Sigma^- \rightarrow n) = -.34 \pm .02, \quad (33)$$

$$F - D = \Delta d(p) - \Delta s(p) = G_A^{exp}(n \rightarrow p) - \sqrt{6}G_A^{exp}(\Sigma \rightarrow \Lambda) = -.19 \pm .04, \quad (34)$$

of which we prefer the second one when we postulate $\alpha_D^{ax} = \alpha_D^{mag}$, remains largely open. The intriguing possibility can, however, be mentioned that the numerical value of the $G_A^{exp}(\Sigma^- \rightarrow n)$, coinciding with Eq.(34), was in fact found in [17], if the weak–electric dipole form factor, referred as one of the second class current effects, is included in the joint analysis of all experimental data.

We note in passing, that the production of the axial – vector meson composed of strange quark-antiquark pairs in antinucleon annihilation may also be useful to probe the strange content of the nucleon and the dynamics of the OZI rule violation. The $q + (\bar{s}s)$ - configuration with $J^P = \frac{1}{2}^+$ composing in part the nonstrange constituent quark can evolve via a chain of transitions

$$q + (\bar{s}s)_{vac} \rightarrow (\bar{s}q)_{0^-} + s \rightarrow q + (\bar{s}s)_{J^{PC}} \quad (35)$$

with $J^{PC} = 0^{++}, 1^{++}, 1^{+-}$. A simple recoupling of the angular momenta enable, through the pertinent Clebsch–Gordan coefficients, to obtain then the ratio

$$w(1^{++}) : w(1^{+-}) : w(0^{++}) = 2 : 1 : 1 \quad (36)$$

which may serve as a qualitative measure of relative yields of corresponding meson states, composed mainly of the "strange matter". The relevant mesons with $J^P = 1^+$ might be the $f_1(1420; 1^{++})^-$ or $f_1(1510; 1^{++})^-$ and $h_1(1380; 1^{+-}(?))^-$ -resonances [1].

3 Remarks

1. The deviation of the ratio $F/D = .75$, Eq.7, from the $SU(6)$ –value $2/3$ shows, that despite the validity of the celebrated $SU(6)$ –ratio [9] $\mu(P)/\mu(N) = -3/2$, the $SU(6)$ –symmetry is strongly broken. The importance of taking into account the nonvalence degrees of freedom in relevant parametrization of the observables within the (broken) internal symmetries is demonstrated

2. The real meaning of all failures (and relative successes, of course) of the "naive" NRQM results (e.g.[8]), coinciding with values from Eqs.(20)–(22), is the neglect of contributions due to the nonvalence degrees of freedom (the sea partons and/or meson clouds at the periphery of hadrons).

3. The strange current quarks considered as a part of the constituent quark internal structure should be explored by the probes with the resolution capability comparable with the constituent quark size, i.e. in the processes with high enough momentum transfers or the energy release. The OZI–rule violating ϕ - meson production in the proton–antiproton annihilation gives further evidence of the polarized strange quark sea inside the polarized nucleon.

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